BEHAVIOUR OF GFRP RETROFITTEDRECTANGULAR RC BEAMS WITH SMALL WEB OPENINGS UNDER TORSION: EXPERIMENTAL STUDY

MANDALA VENUGOPAL

Department of Civil Engineering
National Institute of Technology, Rourkela
Rourkela-769 008, Odisha, India

BEHAVIOUR OF GFRP RETROFITTED RECTANGULAR RC BEAMS WITH SMALL WEB OPENINGS UNDER TORSION: EXPERIMENTAL STUDY

A THESIS SUBMITTED IN PARTIAL FULFILMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Structural Engineering

By

MANDALA VENUGOPAL
(Roll No. 212CE2048)

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
ROURKELA – 769 008, ODISHA, INDIA

BEHAVIOUR OF GFRP RETROFITTED RECTANGULAR RC BEAMS WITH SMALL WEB OPENINGS UNDER TORSION: EXPERIMENTAL STUDY

A THESIS SUBMITTED IN PARTIAL FULFILMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Structural Engineering

By

MANDALA VENUGOPAL

(212CE2048)

UNDERGUIDENCE OF

Prof ASHA PATEL

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769 008, ODISHA, INDIA

June 2014

Department of Civil Engineering
National Institute of Technology, Rourkela
Rourkela – 769 008, Odisha, India

CERTIFICATE

*This is to certify that the Thesis Report entitled "**BEHAVIOUR OF GFRP RETROFITTED RECTANGULAR RC BEAMS WITH SMALL WEB OPENINGS UNDER TORSION: EXPERIMENTAL STUDY**", submitted by **Mr. MANDALA VENUGOPAL bearing Roll no. 212CE2048** in partial fulfillment of the requirements for the award of **Master of Technology in Civil Engineering** with specialization in "**Structural Engineering**" during session 2012-2014 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.*

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

Place: Rourkela

Date: -

Prof. ASHA PATEL
Dept. of Civil Engineering
National Institute of Technology
Rourkela – 769008

ABSTRACT

Provision of utility and service ducts are important part of modern building construction. To facilitate fast and uninterrupted progress the layout of these ducts are planned in advance. Their positions are decided considering the head room provisions in buildings, aesthetic look etc. without jeopardizing the strength,stability and serviceability of the structures. To fulfil these aspects many times ducts have to pass through main load bearing elements like beams.

Web openings in a beam adversely affect its strength and stiffness resulting in excessive deflections which may lead to unpleasant appearance and the collapse of the structure. Therefore, such beams are required to strengthen to restore their strength. The newly developed technique of jacketing the deficit beam with layers of Fiber Reinforced Polymer has proven to be very efficient in restoring and increasing the strength of the beams.

Since 1980 extensive research has been carried out on beams with rectangular and circular openings under the most commonly encountered loading case of shear and flexure. The behavior of beams with openings under torsion and its combination with shear and flexure has not been explored much.

Hence the aim of the present work is to explore the behavior of rectangular RCC beams with small circular and rectangular openings under torsion. The torsional capacity of beams with openings are extracted experimentally .The study is extended by retrofitting the beams with four layers of bidirectional woven GFRP fabric applied following three different orientations scheme 90/90/90/90 ,45/45/45/45 and 90/45/90/45. The restoring torsion capacity, crack patterns are observed.

The experimentally found torsion moment is compared with values calculated from modified ACI code torsion equation proposed by Mansur, M.A. and Hasnat[3] and found to be in good agreement.The retrofitting scheme with GFRP layer orientation 90/45/90/45 proved to be best scheme by providing maximum restoring torsion capacity and better ductility.

ACKNOWLEDGEMENT

The satisfaction and euphoria on successful completion of any task would be incomplete without the mention of the people who made it possible whose constant guidance and encouragement crowned out effort with success.

I would like to express my heartfelt gratitude to my esteemed supervisor, **Prof Asha Patel** for her technical guidance, valuable suggestions, and encouragement throughout the experimental and theoretical study and in preparing this thesis. It has been an honour to work under **Prof.Asha Patel**, whose expertise and discernment were key in the completion of this project.

I am grateful to the **Dept. of Civil Engineering, NIT ROURKELA,** for giving me the opportunity to execute this project, which is an integral part of the curriculum in M.Techprogramme at the National Institute of Technology, Rourkela.

Many thanks to my friends who are directly or indirectly helped me in my project work for their generous contribution towards enriching the quality of the work. I would also express my obligations to Mr.S.K.Sethi, Mr.R.Lugun&Mr.Sushil, Laboratory team members of Department of Civil Engineering, NIT, Rourkela and academic staffs of this department for their extended cooperation.

This acknowledgement would not be complete without expressing my sincere gratitude to my parents for their love, patience, encouragement, and understanding which are the source of my motivation and inspiration throughout my work. Finally I would like to dedicate my work and this thesis to my parents.

MANDALA VENUGOPAL

TABLE OF CONTENT

Page

LIST OF FIGURES:-

LIST OF GRAPHS:-

LIST OF TABLES:-

NOTATIONS

T_{ch}	Torsional strength of plain concrete for beam with opening
T_{sh}	Torsional strength provided by stirrups for beam with opening
f'_c	Cylinder compressive strength
b	Width of the beam
d	Depth of the beam
λ	Nondimensional factor $= \cos 45^0$ for circular opening $=1$ for rectangular opening
d_0	Depth of the opening
f_{ck}	Cube compressive strength of concrete
f_r	Flexural strength of concrete

ACRONYMS AND ABBREVATIONS

ACI	American Concrete Institute
IS Codes	Indian Standard Codes
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
CFRP	Carbon Fiber Reinforced Polymer
HYSD	High-Yield Strength Deformed
CB	Control beam
BSCO	Beam with single circular opening
BTCO	Beam with two circular opening
BSRO	Beam with single rectangular opening
BTRO	Beam with two rectangular opening
BTCOG1	Beam with two circular opening with GFRP$[90/90]_2$
BTCOG2	Beam with two circular opening with GFRP$[45/45]_2$
BTCOG3	Beam with two circular opening with GFRP$[90/45]_2$
BTROG1	Beam with two rectangular opening GFRP$[90/90]_2$
BTROG2	Beam with two rectangular opening GFRP$[45/45]_2$
BTROG3	Beam with two rectangular opening GFRP$[90/45]_2$

CHAPTER 1
INTRODUCTION
1.1 OVER VIEW
Nowadays openings in floor beams become necessary to provide service lines like water supply lines, electricity, computer network ,air conditioning ducts etc to pass through in order to save the story height specially in multi story buildings. Openings also reduce dead weight of structures causing cost savings and systematically placed utility duct improve aesthetic appearance.

The transverse openings through beams are a source of potential weakness. When the service systems are pre-planned , and necessary layout of pipes and ducts are decided well in advance then elements carrying them should be designed to ensure adequate strength and serviceability by following the method described in the different codes.

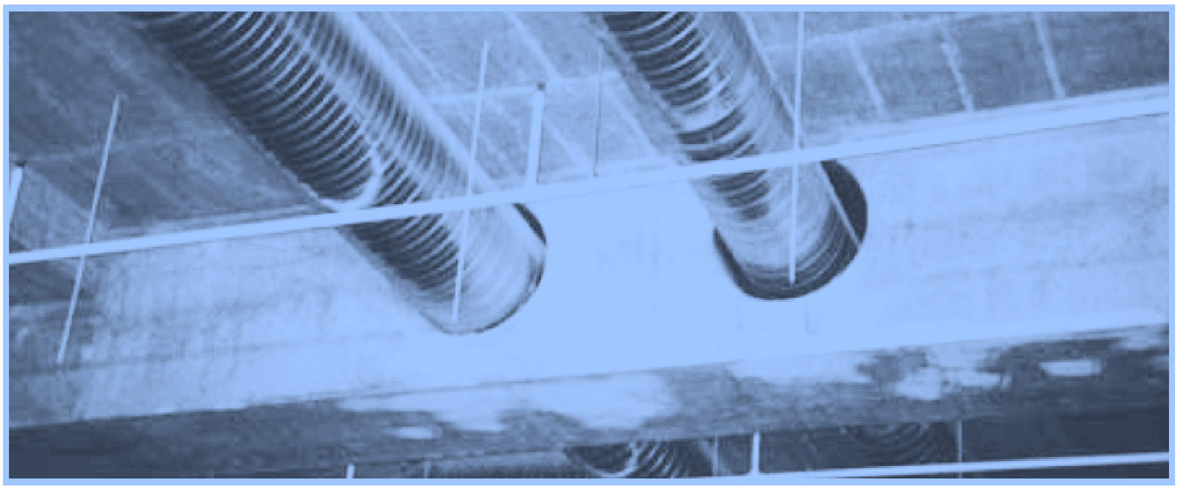


FIG 1.1 Opening In The Beam(Vladimir Cervenka).

However, this may not always be the case. While laying the ducts in a newly constructed building, the Mechanical & Electrician contractor frequently comes up with the request to drill an opening for the sake of simplifying the arrangement of pipes. When such a request comes, the structural designer finds it difficult to give a decision because he would have to take the risk of jeopardizing the safety and serviceability of the structure.

Another situation arises in an old building where concrete cores are taken for structural assessment of the building. If the structure is to stay, then it is needed to repair it adequately to restore the original level of safety and serviceability .

In the past, a lot of research had been carried out to study the behavior of reinforced concrete beams with transverse openings. The investigations dealt with the behavior of reinforced concrete beams with transverse rectangular and circular opening under different combinaions of flexure, shear and torsion. Two types of transverse openings had been investigated, the small and large opening.The classification is based on profile of opening. For rectangular Opening if depth of opening is less than or equal to 0.25 time overall depth then it is called small opening otherwise called Large Opening. For circular opening if diameter of the opening is less than 40% of the overall depth of beam then called small opening ,otherwise called Large Opening.

An opening creates discontinuity in the normal flow of stresses ,thus leading to stress concentration at edges of the opening and leading to early cracking of concrete.To avoid this special reinforcement enclosing the opening should be provided in the form of external or internal reinforcement Internal reinforcements are steel bars provided along with the main reinforcements during casting. External reinforcements are applied externally around opening in the form of jacketing of composite materials like glass fibre or carbon fibre reinforced polymer called GFRP or CFRP.

Fiber-reinforced polymer (FRP) is a composite material made of a polymer matrix reinforced with fibers. The fibers are usually glass or carbon fiber,while the polymer is usually an epoxy. Glass fiber fabrics are highly effective for strengthening of RC beams because of its flexible nature and ease of handling and application, combined with high tensile strength weight ratio and stiffness.

FRP sheets are currently being studied and applied around the world for the repair and strengthening of structural concrete members. FRP composite materials are of great interest because of their superior properties such as high specific stiffness and specific strength as well as ease of installation when compared to other repairing materials. Also, the non-corrosive and nonmagnetic nature of the materials along with its resistance to chemicals makes FRP an excellent option for external reinforcement.

Research reveals that strengthening using FRP provides a substantial increase in post-cracking stiffness and ultimate load carrying capacity of the members subjected to flexure, shear and torsion.

Lot of investigations has been done to determine effect of openings on shear and flexural behavior of RCC beam of different types like rectangular, T-beam, deep beam etc. . Very few works have been done to find the effect of openings on torsional behavior of RCC beam. Many research works are published on behavior of beams with opening retrofitted with different types of FRP of different configurations and orientations under shear and flexure. Very limited works are published for retrofitted beams with openings under torsion.

1.2 Objective

Hence the aim of the present work is to experimentally study the effect of small openings of rectangular and circular types on torsional behavior of rectangular RCC beam. The work is further extended by retrofitting the beams by GFRP fabrics. The variables considered are shape and number of openings on non-strengthen beams and orientation of GFRP fabrics in retrofitted beams containing rectangular and circular openings. In the present work the ratio torsion moment/ flexural moment adopted is one for all beams. The results obtained from experiments are compared with the modified ACI torsion equation proposed by Mansur, M.A. and Hasnat[3].Good correlation is observed between experimental and observed values.

1.3Methodology

For the study eleven beams of same dimensions were cast in the Structural Engineering Laboratory of Civil Engineering Department.

All beams were divided into two series. First series were cast with circular opening whereas second were cast with rectangular openings of same cross sectional area. One beam without web openings was also cast and treated as control beam.

Each series consisted of five beams; first beam had centrally located single opening and remaining four were cast with two symmetrically located openings. The three beams with two openings of both series were retrofitted with bi-directional GFRP fabric.

The retrofitting was done with four layers of GFRP fabric oriented in different directions. The orientation scheme adopted were 90/90/90/90, 45/45/45/45 and 90/45/90/45.

All beams were tested under monotonically increasing static loads on both arms of projected parts simultaneously, this arrangement transferred torsion to the middle part of the beam. All beams were tested under torsion till failure.

During testing loads were applied in increments and at each increment deflections were observed across the section to calculate twisting angle at different points on the beam.

During testing cracks formation and their propagation and inclinations were critically observed. For retrofitted beams crack patterns and failure pattern were observed after removing the GFRP from the beams.The experimentally determined values were compared with analytical values obtained from modified torsion equation proposed by ACI Code.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review On Torsional Strengtheningof RC Beams With Opening:-

SoroushAmiri, Reza Masoudnia and Ali Akbar Pabarja (2011) carried out study on behavior of reinforced concrete beams with rectangular and circular openings and precast beams with rectangular and circular openings was investigated. Then effects of the size and location of the openings on the behavior of such beams are examined.

M.A. Mansur[9] September (2006), gave a comprehensive overview on the analysis and design of reinforced concrete beams contain transverse openings and subjected to a combined bending and shear. Recognizing the differences in beam behaviors, circular and large rectangular openings were treated separately. Practical situations of drilling openings in existing beams are treated with special design consideration. Beams with multiple openings were also briefly explained by author.

Ameli et al[15]. (2007) had experimentally investigated reinforced concrete beams subjected to torsion and strengthened with an FRP wraps in a different configurations. Experimental results showed that FRP wraps increase the ultimate torque of an fully wrapped beams considerably and in addition enhancing ductility. They also provide a numerical study on the retrofitted beams under torsion.

Abdallaa et al [17](2003) used fiber reinforced polymer (FRP) sheets to strengthen the opening region in an experimental program'.

Thompson and Pessiki (2006) conducted an experimental study to investigate the behavior of precast, pre-stressed inverted-tee girders with a large web openings under bending.

Mansur[9] (1998) discussed the effects of introducing an transverse opening in the beams, When no additional reinforcement was provided in the members above and below the opening (chord members), tests conducted by **Siao and Yap (1990)** have shown that beams fail prematurely by sudden formation of diagonal crack in the compression chord.

Somes and Corley[4] (1974), defined small and large opening on the basis of experimental and analytical study. The study was confined to circular opening. A circular opening was considered as large opening when its diameter exceeds 0.25 times the depth of the web. .

Salam[17] (1977) conducted an investigation on beams of rectangular cross section tested under two symmetrical point loads. Moreover, **Mansur et al (1991)** an experimental carried out an investigation on eight reinforced concrete continuous beams, each containing a large transverse opening. Their study were showed that increase in depth of opening from 140 mm to 220 mm led to reduction in collapse load from 240 kN to 180 kN.

AbulHasnat and Aii A.Akhtanizzamam[1] proposed a set of generalized strength equations based on the skew bending model , developed to predict torsional strength and failure mode of reinforced concrete beams with or without a small transverse opening. Twenty-four rectangular reinforced-concrete beams containing a transverse opening of constant dimensions were grouped into four different series and were tested under various combinations of torsion, bending, and shear.

Hasnat et al (1993)[11] had tested seventeen pre-stressed concrete beams without stirrups containing transverse circular opening. In this research investigations were carried out on beams having two openings of different diameters and subjected to various combinations of torsion and bending.

Ghobarah[18] et al. (2002) was conducted a experimental investigation on the improvement of the torsional resistance of reinforced concrete beams using fiber-reinforced polymer (FRP) fabric. A total of eleven beams was tested. Three beams was designated as an control specimens and eight beams was strengthened by an FRP wrapping of different configuration and tested. Both glass and carbon fibers was used in torsional resistance upgrade. The effectiveness of an various wrapping configurations exhibited that fully wrapped beams performed better than using strips. The 45° orientation of the fibers ensures that the material is efficiently utilized.

Panchacharam and Belarbi[19] (2002) had experimentally found that externally bonded GFRP sheets can significantly increases both the cracking and ultimate torsional capacity of RCC beams. The behaviour and performance of reinforced concrete member strengthened with externally bonded Glass FRP (GFRP) sheets subjected to pure torsion was presented.

The variables considered in the experimental study include the fiber orientation, the number of beam faces strengthened (three or four), the effect of number of FRP plies used, and the influence of anchors in U-wrapped test beams. Experimental results revealed that externally bonded GFRP sheets can significantly increases both the cracking and the ultimate torsional capacity.

Ameliand Ronagh (2007); Hii and Al-Mahadi[20] (2006); Rahal and Collins[21] (1995). **Santhakumar et al. (2007)** ,their works comprised of experimental and numerical study of un-retrofitted and retrofitted solid reinforced concrete beams subjected to combined bending and torsion. Different ratio between twisting moment and bending moment were considered. The finite elements analysis by using ANSYS software were adopted for the study. Then the study was extended to explore the behaviour of reinforced concrete beams retrofitted with carbon fiber reinforced plastic composites with an 0/45and 0/90 fiber orientations. The study revealed that the CFRP composites with 0/45 fiber orientations was more effective for retrofitting an RC beams subjected to combined bending and torsion.

Zojaji and Kabir (2011) developed a new computational procedure to predict the full torsional response of reinforced concrete beams strengthened with Fiber Reinforced Plastics (FRPs), based on the Softened Membrane Model for Torsion (SMMT). To validate the proposed analytical model, torque-twist curves was obtained from the theoretical approaches are compared with experimental ones for both solid and hollow rectangular sections.

Rubinsky[13] (1954) and Wines, J. C. et al., (1966) , had started research on FRP maerial and its application on concrete structures.. Their pioneering work on bonded FRP system can be credited to Meier (Meier 1987); this work led to an first on-site repair by the bonded FRP in Switzerland (Meier and Kaiser (1991).Japan developed the first FRP applications for repair of the concrete chimneys in an early 1980s..By 1997 more than 1500 concrete structures worldwide have been strengthened with externally bonded FRP materials. Thereafter, many FRP materials with different types of fibres have been developed.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 MATERIAL PROPERTIES

3.1.1. Concrete

A mix of concrete of M_{20} grade is designed by using Portland Slag cement of Konarkbrand , locally available sand confirming to Zone III and 20 mm down size aggregate for a slump of 30mm. The mix is designed following IS 10262:2009 Code.

The proportion of design mix adopted for the experiment is 1:1.7:3.8 by weight and water cement ratio is taken as 0.6.

Table 3.1Properties of Concrete after 28 days

Beams	Compressive Strength N/mm^2		Tensile Strength N/mm^2	
	Cube *fck*	**Cylinder *fc***	**Split Tensile Strength**	**Flexural Strength Of Concrete *fr***
CB	20.89	18.40	2.72	2.65
BSCO	26.44	20.40	2.80	3.20
BTCO	26.88	21.60	2.30	3.30
BSRO	29.33	20.00	2.50	3.25
BTRO	29.55	19.20	2.70	3.20
BTCOG1	30.00	27.12	2.79	3.10
BTCOG2	30.67	21.50	2.20	3.20
BTCOG3	30.20	22.64	2.65	3.20
BTROG1	30.22	21.50	2.79	2.90
BTROG2	30.00	20.30	2.37	3.10
BTROG3	30.40	23.77	3.07	3.20

3.1.2 Reinforcing Steel

HYSD Steel bars of Fe415 grade of 8mm,10mm,12mm and 16mm diameter are used for reinforcement. All bars are tested for Tensile strength and they comply with the code IS 1786-.1985

Table 3.2 Tensile Properties of Reinforcing steel bars

Diameter of Bar mm	0.2% Proof Stress N/mm^2	Ultimate Tensile Strength N/mm^2	% Elongation	Remark
8	524	673.04	22.50	All bars are complied with IS 1786-1985
	522	663.28	22.50	
	555	656.24	22.50	
10	535	680.47	20.00	
	524	664.86	20.00	
	558	659.82	20.00	
12	595	702.30	23.33	
	572	680.63	20.00	
	536	706.60	23.33	
16	496	665.72	22.50	
	490	701.23	22.50	
	478	633.43	22.50	

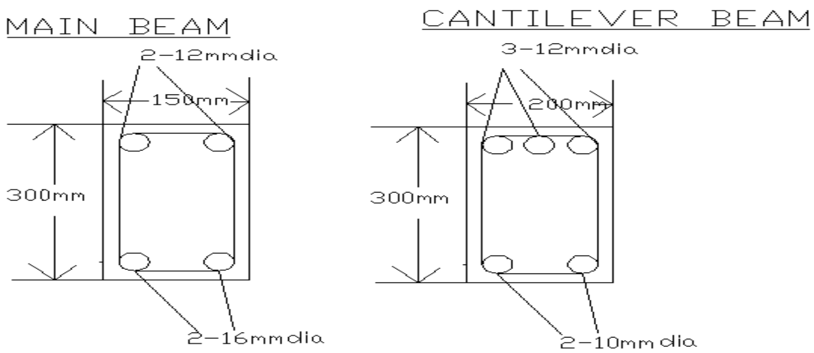


Fig 3-1 Reinforcement Detailing of Beams

3.1.3 Fiber Reinforced Polymer (FRP)

Fiber reinforced materials with polymeric matrix (FRP) can be considered as composite, They are heterogeneous, and anisotropic materials with a prevalent linear elastic behaviour up to failure. Normally, Glass and Carbon fibres are used as reinforcing material for FRP. For present study bidirectional woven GFRP fabric was used.

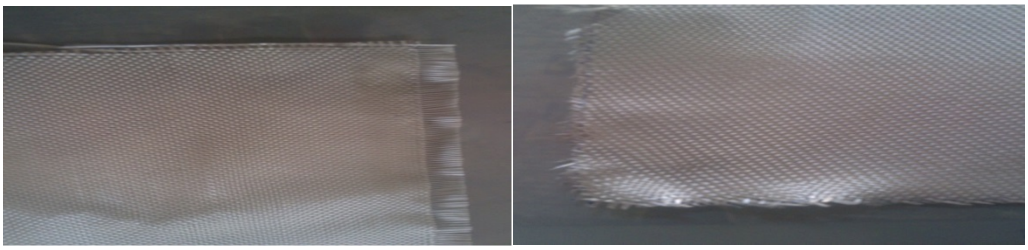


FIG 3.2 a)GFRP fabrics in [90/90^0] **b) GFRP fabrics in [45^0/45^0]**

3.1.4 Epoxy Resin

Epoxy Resins was used to glue the layers of GFRP fabric and also used to stick the fabric to concrete surface. The success of strengthening technique primarily depends on the performance of the epoxy resin used for bonding of FRP to concrete surface. Numerous types of epoxy resins with a wide range of mechanical properties are commercially available in the market.

These epoxy resins are generally available in two parts, a resin and hardener. The resin and hardener was used in present study are Araldite LY 556 and hardener HY 951 respectively. Both the parts are mixed in 1:1 proportion.

To study the tensile properties of composite, standard coupons (250mm long x 25 mm wide) were prepared by using different layers of GFRP and epoxy Resin. The tensile test was performed on INSTRON UTM machine at the laboratory.

TABLE 3.3 TENSILE PROPERTY OF GFRP FABRIC

GFRP Coupon	Thickness of coupon mm	Ultimate stress N/mm^2	Ultimate load in kN	Young's modulus N/mm^2
2 layers	0.86	298	6.694	9839
4 layers	1.73	296	12.540	10040

Fig 3.3 Roller Used To Remove Air Bubbles

3.2 Casting of Specimens:-

All beams are of same dimensions, having same reinforcements. All beams are designed to fail in torsion hence no stirrups are provided except at each end to keep longitudinal reinforcements in positions. The dimension of specimen beam is shown in Fig.

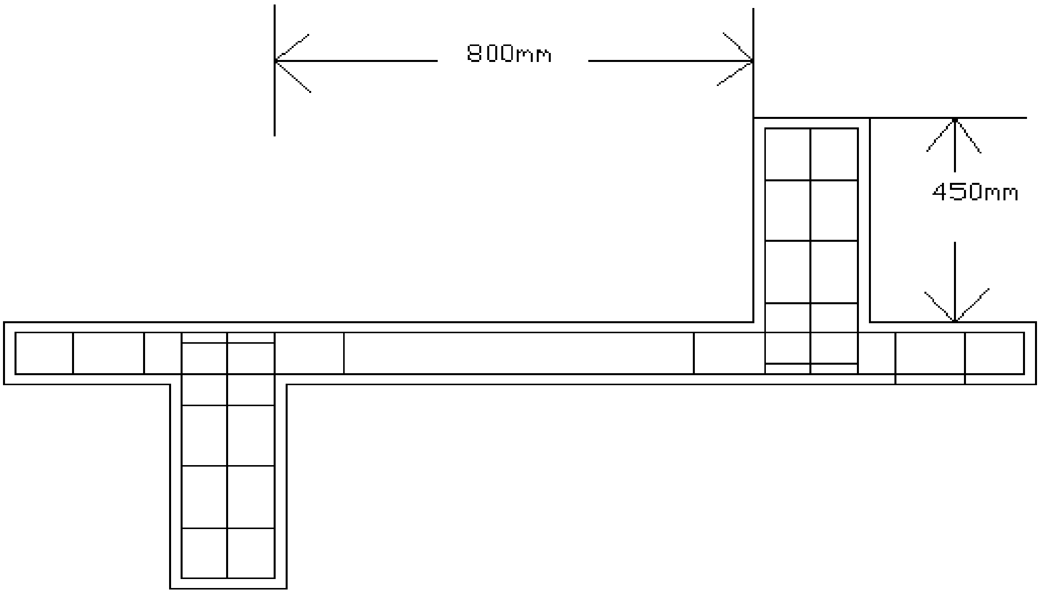


Fig 3.4 Casting ofthe Beam View

Beam was cast with circular/rectangular moulds to provide the opening in the transverse direction. These moulds were removed after 24 hours. Beam was removed from the mould next day and watered and covered with damped jute bags for curing for 28 days. Along with beam, standard specimens to determined properties of concrete, these include three no. of cubes (150mmx150mmx150mm), cylinders (150mm dia x300mm) and prisms (100mmx100mmx500mm).They were tested after 28 days for cubical compressive strength f_{ck}, cylindrical compressive strength f_c , modulus of rupture $f_r$and split tensile strength.

Three beams in each cases were strengthen by sticking four layers of GFRP fabric in different orientations as per the scheme. While sticking the fabrics care had been taken to remove the air pockets within the layers. After sticking fabrics beams were left for 48 hours to allow the composite to set.

3.3 STRENGTHENING OF BEAMS

To stick the GFRP fabric , the concrete surface is made rough using a coarse sand paper and then cleaned with an air blower to remove all dirt and debris. The mixing of resin and hardener are carried out in a plastic mug container. The GFRP fabric are cut according to the size . A layer of epoxy resin was uniformly applied to the concrete surface of beam and a layer of GFRP fabric in pre decided direction is glued to the concrete surface, once it is properly placed further epoxy resin is applied and the next layer of GFRP fabric in required direction is glued to the beam. The procedure is adopted to stick all layers. After application of each layer ,a roller is used to remove air bubbles entrapped at the epoxy/concrete or an epoxy / fabric interface .During hardening of the epoxy, a constant uniform pressure is applied to the composite fabric surface in order to extrude the excess epoxy resin and to ensure good contact between the epoxy, the concrete and the fabric. For proper bonding, this operation must be carried out at a room temperature.

3.4 Form Work

The reinforcement cage was then placed inside the formwork carefully with a cover of 35mm on sides and bottom by placing concrete cover blocks.

FIG 3.5 Form Work of Beam

3.5. EXPERIMENTAL SETUP

All beams were tested under monotonically increasing static loads on both arms of projected parts simultaneously, this arrangement transferred torsion to the middle part of the beam of 0.8 m length. The beams were tested under torsion till failure. During testing loads were applied in increments and at each increment deflections were observed across the section to calculate twisting angle at different points on the beam. During testing cracks formation and their propagation and inclinations were critically observed. For retrofitted beams crack patterns and failure pattern were observed after removing the GFRP from the beams.

The standard specimens corresponds to the beam were tested to determine cubical and cylindrical compressive strength and modulus of rupture of concrete.

Fig 3.6Experimental Set-up For Testing

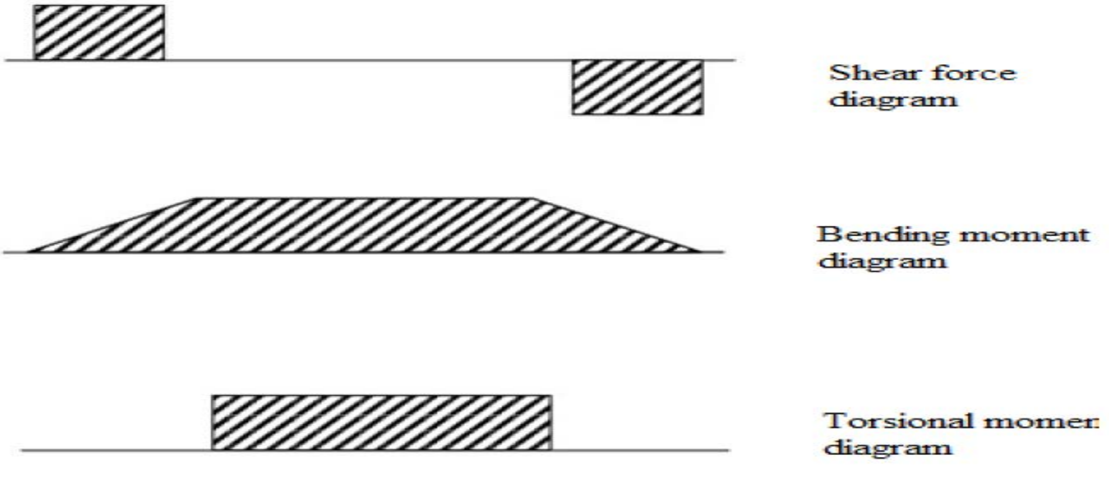


FIG 3.7Shear Force,Bending Moment and Torsional Moment Diagrams

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Testing Of Beams:-

Allthe eleven beams were tested till complete collapse. Two dial gauges were placed along the width of a section to measure deflections in order to calculate angle of twisting moment at the section. Such arrangements were made at sections along the span, below the centre of openings and sections midway between opening and projecting arms. Demac gauges were also fixed on one side vertical face of the beam to measure strains with the help of mechanical strain gauge.Loads were applied in increments. At each increment dial gauges readings and strain gauge readings were noted down. Simultaneously cracks were observed and their propagations were carefully monitored till collapse occurred. The angle of inclination of principal cracks formed was measured.

4.1.1 CONTROL BEAM (CB):-

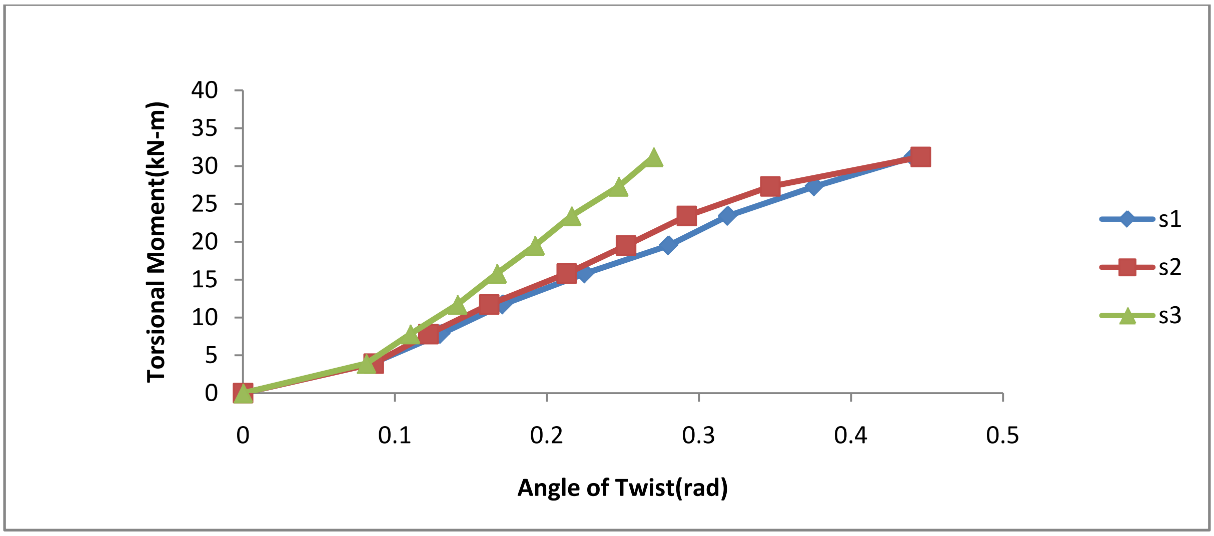
Control beam was beam without opening. Load was applied on the two projected moment arm of the beams which generated torsion in middle 0.8 m long span of the beam.. At each increment of the load, deflections at L/3, L/2 and 2L/3 was observed and noted down with the help of six nos. of dial gauges. At each section two dial gauges were fixed to measure the displacement caused by twisting moment. The relative displacements divided by distance between dial gauges gives angle of twist. Section at L/3 was taken as sec-1, section at middle of beam as taken as sec-2, and section at 2L/3 was taken as section 3.The load at which the first visible crack is developed is recorded as initial cracking load. Then the load is applied till the complete failure of the beam.

FIG 4.1(a)Control Beam CB (b) Crack pattern in Control beam

The initial crack in the CB was appeared at 70KN, and the ultimate load failure of the control beam was at 86KN and torsional moment was 33.54KN-M.A major diagonal crack had formed making 45^0angles with horizontal.

TABLE 4.1 Torsional Moment Vs Angle of Twist for CB

Load kN	Torsional Moment kN-m	Section 1	Section 2	Section 3	Remarks
		Angle of twist(radians)			
0	0	0	0	0	
10	3.9	0.085	0.086	0.081	
20	7.8	0.130	0.122	0.110	
30	11.7	0.171	0.162	0.141	
40	15.8	0.225	0.213	0.167	
50	19.5	0.280	0.252	0.192	
60	23.4	0.319	0.292	0.216	
70	27.3	0.376	0.347	0.247	Initial crack appeared
80	31.2	0.441	0.446	0.270	
86	33.54				Ultimate failure load



GRAPH 4.1 Torsional moment Vs Angle of twist for CB.

4.1.2 BEAM (BSCO):-

This was a Beam with Single Circular Opening at the centre. The diameter of opening was 100mm which as per the specifications are small opening. Extra reinforcement was not provided at the opening in order to study the effect of opening in terms of load carrying capacity. The experimental set up and method of testing was same as in previous case. Two dial gauges were provided at centre of the hole across the width of the section.

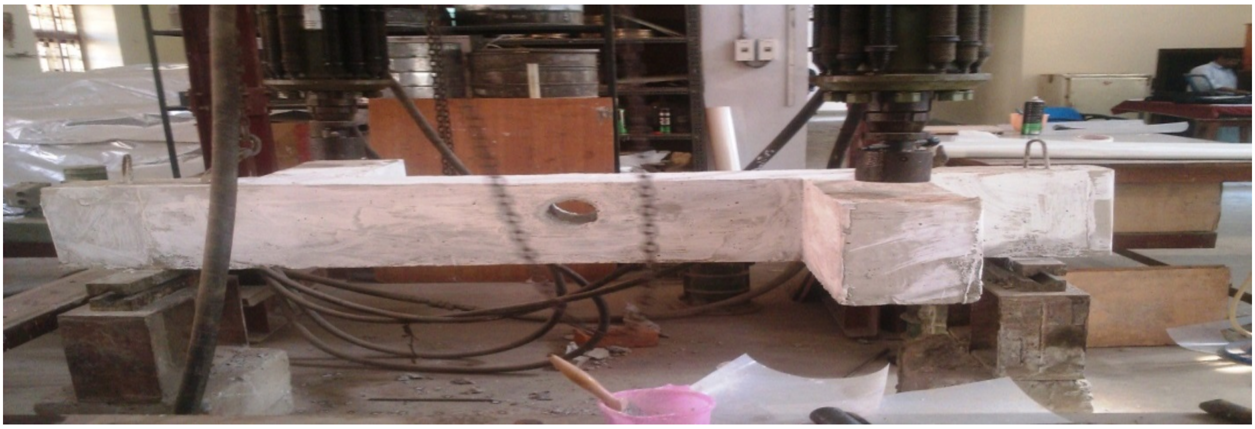


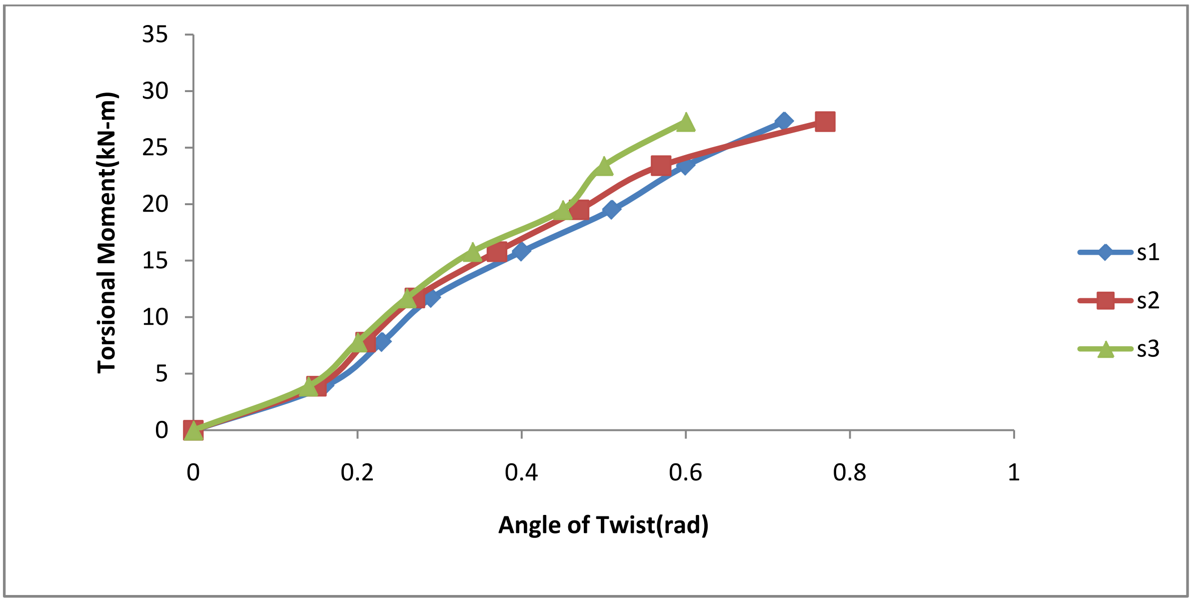
FIG 4.2(a)Beam BSCO

FIG 4.2(b) Crack pattern in BSCO beam

The first crack initiated at load of 60 kN at edge of the opening .Two major cracks formed as shown in the Fig. and propagated diagonally toward edges of the beam along with various inclined cracks. This type of failure is called Frame Type failure. The beam failed at 78 kN load i.e. at 30.42 kN-m torsional moment.It was observed that the cracks were appeared making an angle 40º-50º with the main beam.. As compared to the control beam the percentage reduction in loading was 9.30%.

TABLE 4.2 Torsional Moment Vs Angle of Twist forBSCO

LOAD kN	TORSIONAL MOMENT kN-m	SECTION 1	SECTION 2	SECTION 3	REMARKS
0	0	0	0	0	
10	3.9	0.16	0.15	0.14	
20	7.8	0.23	0.21	0.20	
30	11.7	0.29	0.27	0.26	
40	15.8	0.40	0.37	0.34	
50	19.5	0.51	0.47	0.45	
60	23.4	0.60	0.57	0.50	INITIAL CRACK AT 60kN
70	27.3	0.72	0.77	0.60	
78	30.42				ULTIMATE FAILURE AT 78kN



GRAPH 4.2 Torsional moment Vs Angle of twist of BSCO

Since the reduction in torsional moment capacity for this beam was 9.3% only. It was decided to have two openings instead for better investigation.

4.1.3 BEAM (BTCO):-

This was a Beam with Two Circular Openings symmetrically located. The diameter of openings was 100mm.The experimental set up and method of testing was same as in previous case. Sets of dial gauges were provided below centre of both openings.

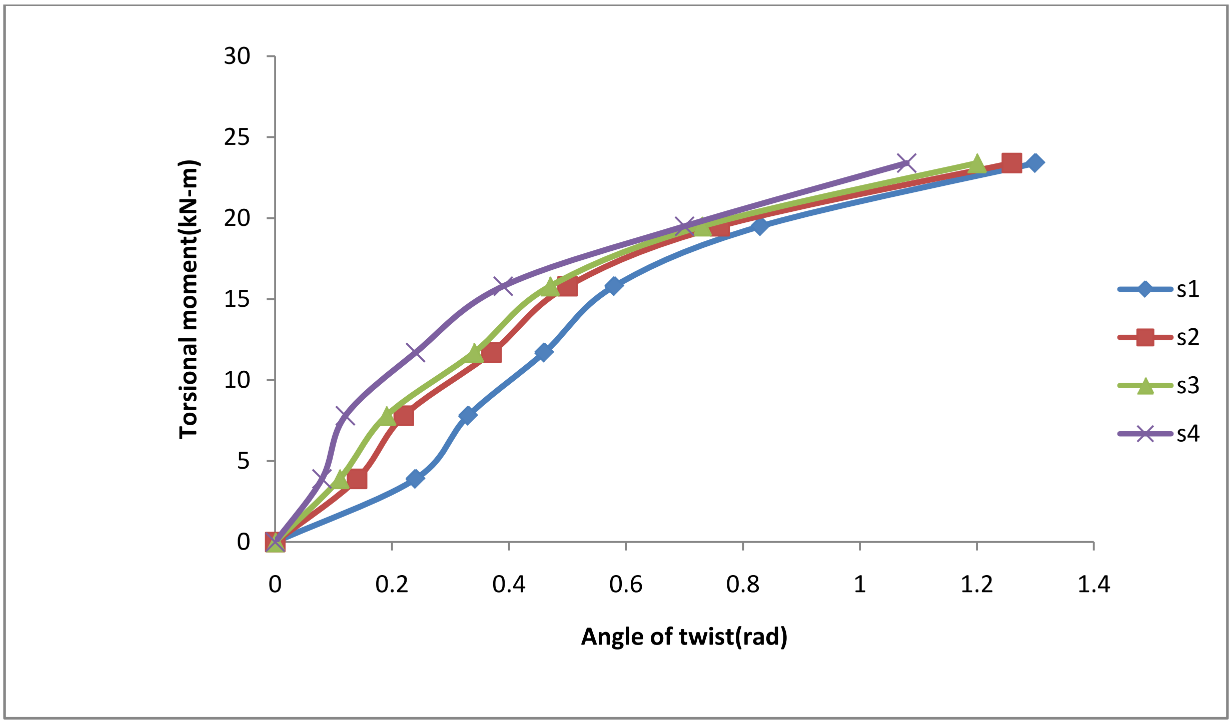
FIG 4.3(a) Beam BTCO

FIG 4.3(b) Crack pattern in BTCO

The first crack initiated at load of 50 kNat top edge of left opening and propagated diagonally towards top .With further increase in loading similar crack initiated at edge of other opening forming a second major diagonal crack along with various inclined cracks as shown in the Fig. The crack pattern exhibited the Frame type of failure prominently showing two cracks..The beam failed at 68 kNload i.e. at 27.3 kNm torsional moment. The cracks were appeared making an angle 40º-50º with the longitudinal edge of beam. As compared to the control beam the percentage reduction in loading was 20.90%.

TABLE 4.3 Torsional Moment vs Angle of Twist for BTCO

LOAD kN	TORSIONAL MOMENT kN-m	SECTION 1	SECTION 2	SECTION 3	SECTION 4	REMARKS
0	0	0	0	0	0	
10	3.9	0.24	0.14	0.11	0.08	
20	7.8	0.33	0.22	0.19	0.12	
30	11.7	0.46	0.37	0.34	0.24	
40	15.8	0.58	0.50	0.47	0.39	
50	19.5	0.83	0.76	0.73	0.70	INITIAL CRACK AT 50kN
60	23.4	1.30	1.26	1.20	1.08	
68	27.3					ULTIMATE FAILURE AT 68kN



GRAPH 4.3 Torsional moment Vs Angle of twist of BTCO

4.1.4 BEAM (BSRO):-

This was a Beam with Single Rectangular Opening at the centre. The size of opening was 110mm long X 72 mm deep ,which as per the specifications are small opening. Extra reinforcement was not provided at the opening in order to study the effect of opening in terms of load carrying capacity. The experimental set up and method of testing was same as in previous case. Two dial gauges were provided at centre of the hole across the width of the section to measure angle of twist.

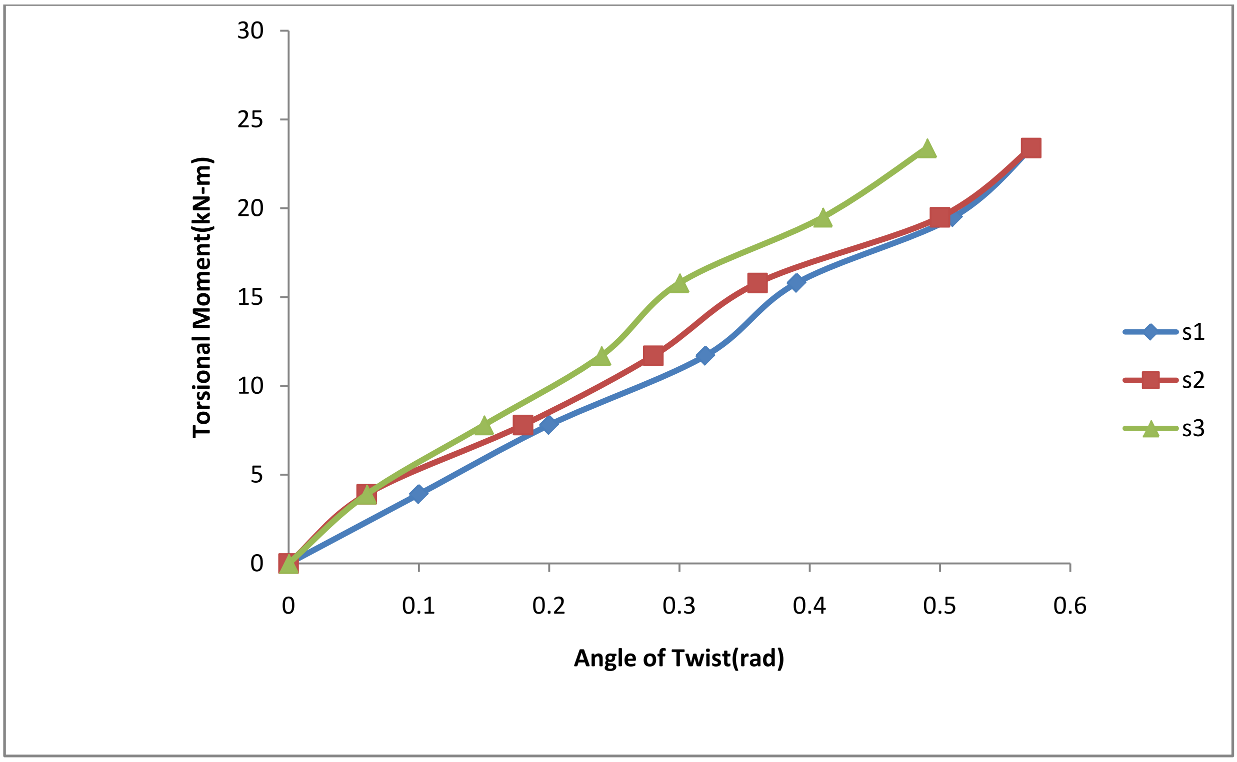
FIG 4.4(a) Crack pattern in BSRO

FIG 4.4(b) Crack pattern on top face of BSRO

The first crack initiated at corner of opening at load of 50 kN and propagated diagonally towards edge. A single prominent diagonal crack formed exhibiting beam type failure. The beam failed at 66 kN load i.e. at 25.7kNm torsional moment.The crack was observed to make 45^0angle The reduction in load carrying capacity was 23.2 % which is more compared with beam with single circular opening of same area. Even the load at which first crack formed was observed less in this case.

TABLE 4.4 Torsional Moment vs Angle of Twist for BSRO

LOAD kN	TORSIONAL MOMENT kN-m	SECTION 1	SECTION 2	SECTION 3	REMARKS
0	0	0	0	0	
10	3.9	0.10	0.06	0.06	
20	7.8	0.20	0.18	0.15	
30	11.7	0.32	0.28	0.24	
40	15.8	0.39	0.36	0.30	
50	19.5	0.51	0.50	0.41	INITIAL CRACK AT 50kN
60	23.4	0.57	0.57	0.49	
66	25.74				ULTIMATE FAILURE AT 66kN



GRAPH 4.4 Torsional moment Vs Angle of twist of BSRO

4.1.5 BEAM (BTRO):-

This was a Beam with Two Rectangular Openings symmetrically located. The size of openings was 110mm x 72 mm . The experimental set up and method of testing was same as in previous case. Sets of dial gauges were provided below centre of both openings hence four sets of dial gauges were used for measuring twist angles.

FIG 4.5(a) BeamBTRO

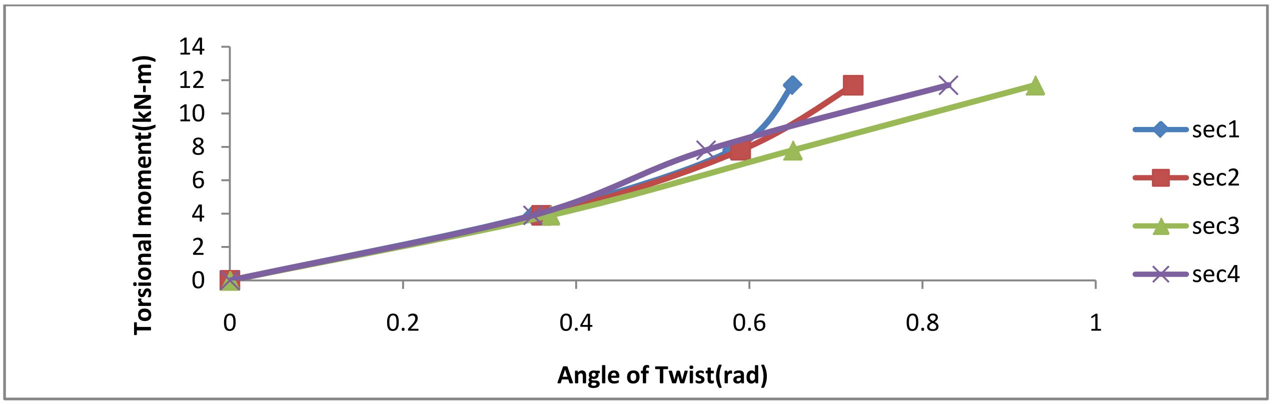
FIG 4.5(b) Crack pattern on one face of BTRO

FIG 4.5(c) Crack pattern on another face of BTRO

The first crack started at load of 28kN. The crack pattern is shown in the Fig. One major diagonal crack formed across the one opening causing failure and spalling of concrete at bottomedge. Complete collapse occurred at 35 kN load i.e. at 13.6kNm torsional moment. The crack made an angle of 48^0 with the edge of the beam. The percentage reduction in strength was found to be 59.3%.

TABLE 4.5 Torsional Moment Vs Angle of Twist for BTRO

Load kN	Torsional Moment kN-m	Section1	Section2	Section3	Section4	Remarks
0	0	0	0	0	0	
10	3.9	0.35	0.36	0.37	0.35	
20	7.8	0.58	0.59	0.65	0.55	
30	11.7	0.62	0.72	0.93	0.83	Initial Crack at 28kN
35						Ultimate Load Failure at 35kN



GRAPH 4.5 Torsional moment Vs Angle of twist of BTRO

The remaining 6 beams (with two openings), threefrom each series are retrofitted with GFRP fabrics. For all beams four layers of Bi-directional GFRP fabric were used. All beams were fully U-jacketed with four layers of GFRP. In each case orientation of layer of fabric were different. The layers orientation considered were (90/90/90/90), (45/45/45/45) and (90/45/90/45). The GFRP were not applied inside the opening. All beams were observed for de-bonding and fracture type of failure. This will help to theoretical analysis of the beams and to validate the experimentally found results.

4.1.6 BEAM (BTCOG1):-

This was a retrofitted **B**eam with **T**wo **C**ircular **O**penings following **1**st scheme of application of GFRPfabrics. The four layers of bi directional GFRP were applied on the beam on three sides forming U-jacket between the cantilever arms. The GFRP across the opening were cut and it was not applied inside the openings.The experimental set up and method of testing was same as in previous case. Sets of dial gauges were provided below centre of both openings. The load, at which first cracking sound was heard, was noted down. After collapse GFRP sheets were removed and crack pattern of beam was observed.

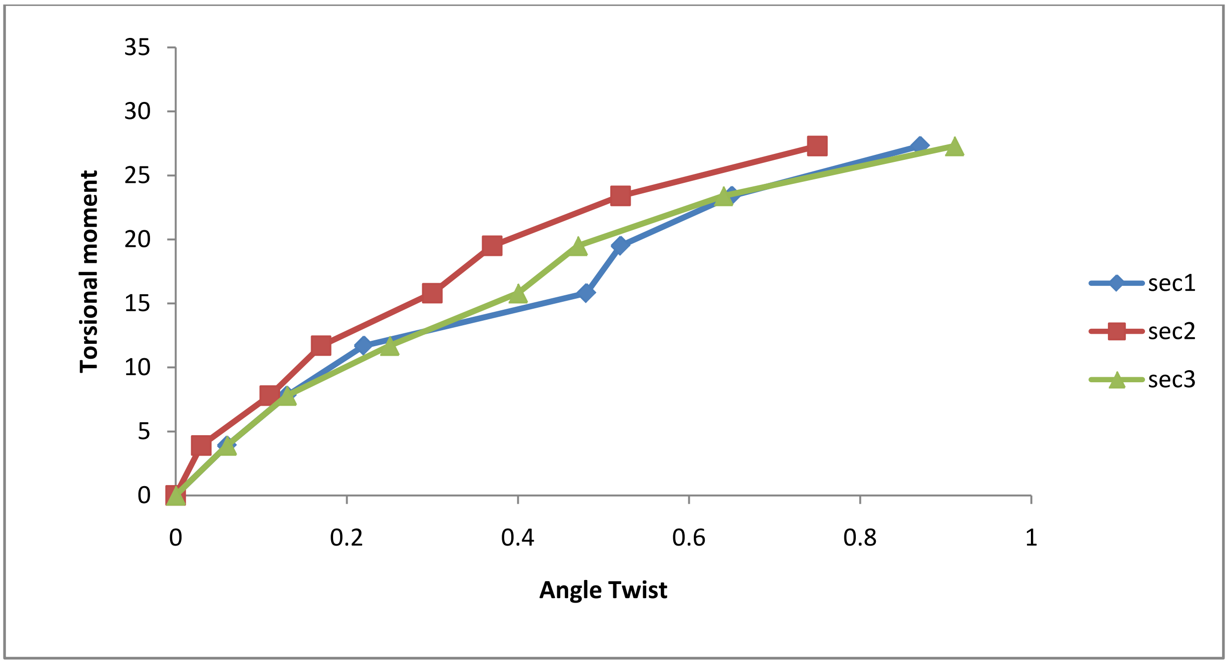
FIG 4.6 Beam**BTCOG1**

FIG 4.6(b) Crack pattern on one face of BTCOG1c) crack pattern on other face of BTCOG1

The first crack initiated from top i.e.-jacketed part of the beam at load of 60kN .With further increase of load it propagated diagonally on top face. The beamultimately failed at 75 kN load i.e. at 29.25kNm torsional moment. After removing the GFRP jacket it was observed that a prominent almost inclined crack has developed, passing through both opening andmaking an angle 50^0. The increase in torsional capacity was found to be 9.3% with respect to corresponding non retrofitted beam BTCO.

TABLE 4.6 Torsional Moment Vs Angle of Twist for BTCOG1

Load kN	Torsional moment kN-m	Section 1	Section 2	Section 3	Remarks
0	0	0	0	0	
10	3.9	0.06	0.03	0.06	
20	7.8	0.13	0.11	0.13	
30	11.7	0.22	0.17	0.25	
40	15.8	0.48	0.30	0.40	
50	19.5	0.52	0.37	0.47	
60	23.4	0.65	0.52	0.64	Initial crack at 60kn
70	27.3	0.87	0.75	0.91	
75	29.25				Ultimate failure at 75kn



GRAPH 4.6 Torsional moment Vs Angle of twist of BTCOG1

4.1.7 BEAM (BTCOG2):-

This was a retrofitted Beam with Two Circular Openings following 2nd scheme of application of GFRP fabrics i.e. (45/45/45/45/45). The layers made 45^0 with longitudinal axis of beam. The method of application of GFRP fabric was same. The experimental set up and method of testing was same as in previous case. After collapse GFRP sheets were removed and crack pattern of beam was observed.

FIG 4.7(a)Beam BTCOG2

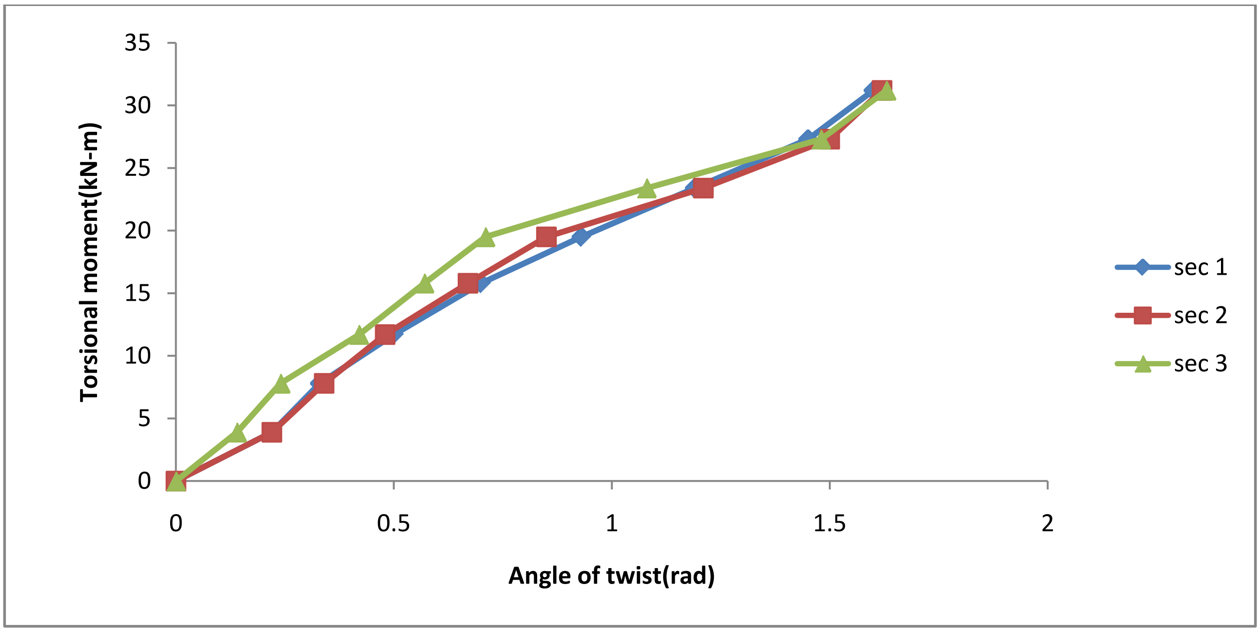
FIG 4.7(b) Crack pattern on one face of BTCOG2

FIG 4.7(c) Crack pattern on other faceof BTCOG2

In this case also major crack had initiated from top i.e.un- strengthened part of the beam at 70 KN load. The beam failed at 85 kN load i.e. at 33.15kNm torsional moment.Removal of GFRP showed **Frame type** of failure. It was observed that the cracks were appeared making an angle 45^0 with the main beam. 20 % increase in torsional moment capacity was observed.

TABLE 4.7 Torsional Moment Vs Angle of Twist for BTCOG2

Load kN	Torsional moment kN-m	Section 1	Section 2	Section 3	Remarks
0	0	0	0	0	
10	3.9	0.22	0.22	0.14	
20	7.8	0.33	0.34	0.24	
30	11.7	0.50	0.48	0.42	
40	15.8	0.70	0.67	0.57	
50	19.5	0.93	0.85	0.71	
60	23.4	1.19	1.21	1.08	
70	27.3	1.45	1.50	1.48	Initial crack 70kN
80	31.2	1.60	1.62	1.63	
85					Ultimate load 85kN



GRAPH 4.7 Torsional moment Vs Angle of twist of BTCOG2

4.1.8 BEAM (BTCOG3):-

This was again a retrofitted Beam with Two Circular Openings following 3rd scheme of application of GFRP fabrics i.e. (90/45/90/45). The first and third layers made 90^0 ,second and fourth layers made 45^0 with longitudinal axis of beam. The method of application of GFRP fabric was same . The experimental set up and method of testing was same as in previous case. After collapse GFRP sheets were removed and crack pattern of beam was observed.

FIG 4.8 a) setup Of Two Circular Opening With GFRP(BTCOG3)

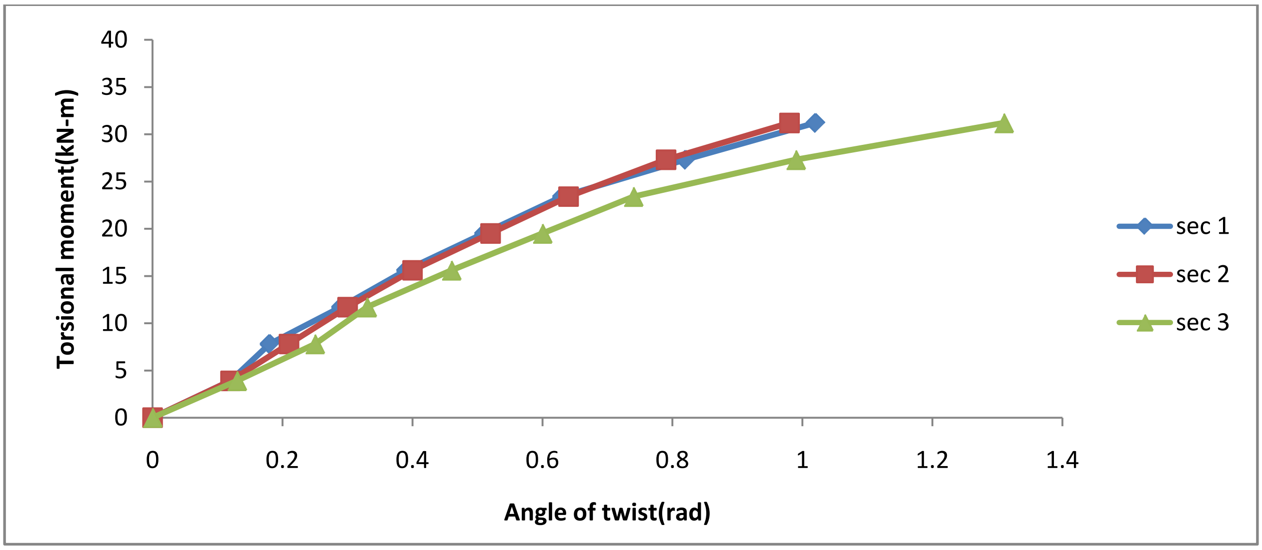
FIG 4.8(b) Crack pattern on one face of BTCOG3

FIG 4.8(c) Crack pattern on other face of BTCOG3

In this case also major crack had initiated from top i.e.un- strengthened part of the beam at 75kN load. The beam failed at 90 kN load i.e. at 35.1 kN-m torsional moment. Removal of GFRP showed multiple cracks formation with spilling of concrete on vertical faces. It was observed that the major cracks were appeared making an angle 55^0 with the main beam and 24.4 % increase in torsional moment capacity was observed.

TABLE 4.8 Torsional Moment Vs Angle of Twist for BTCOG3

Load kN	Torsional moment kN-m	ANGLE OF TWISTING			
		Section 1	Section 2	Section 3	Remarks
0	0	0	0	0	
10	3.9	0.12	0.12	0.13	
20	7.8	0.18	0.21	0.25	
30	11.7	0.29	0.30	0.33	
40	15.6	0.39	0.40	0.46	
50	19.5	0.51	0.52	0.60	
60	23.4	0.63	0.64	0.74	
70	27.3	0.82	0.79	0.99	Initial crack 75kN
80	31.2	1.02	0.98	1.31	
90	35.1				Ultimate load 90kN



GRAPH 4.8 Torsional moment Vs angle of twist of BTCOG3

4.1.9 BEAM(BTROG1):-

This was a retrofitted **B**eam with **T**wo **R**ectangular **O**penings following **1**st scheme of application of GFRP fabrics i.e. 90/90/90/90. The method of application of GFRP fabric was same. The experimental set up and method of testing was same as in previous cases. Sets of dial gauges were provided below centre of both openings. The load at which first crack appeared was noted down. After collapse GFRP sheets were removed and crack pattern of beam was observed.

Similar to previous cases for retrofitted beams in this case also initial crack at 60 kN load was observed at top which was not covered with GFRP fabric. The beam failed at 70 kN load i.e. at 27.3 kNm torsional moment. Removal of GFRP showed beam type of failure. It was observed that the major cracks made an angle 48^0 with the longitudinal axis of main beam and 50 % increase in torsional moment capacity was obtained.

FIG 4.9(a)Beam BTROG1

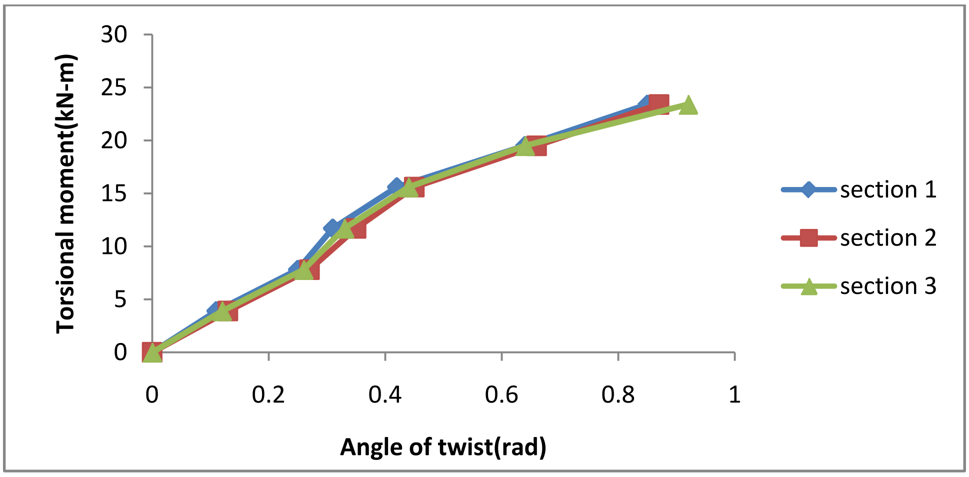
FIG 4.9(b) Crack pattern on one face of BTROG1

FIG 4.8(c) Crack pattern on other side of BTROG1

TABLE 4.9 Torsional Moment Vs Angle of Twist for BTROG1

Load kN	Torsional moment kN-m	Section 1	Section 2	Section 3	Remarks
0	0	0	0	0	
10	3.9	0.11	0.13	0.12	
20	7.8	0.25	0.27	0.26	
30	11.7	0.31	0.35	0.33	
40	15.6	0.42	0.45	0.44	
50	19.5	0.64	0.66	0.64	Initial crack 50kN
60	23.4	0.85	0.87	0.92	
70	27.3				Ultimate load at 70kN

GRAPH 4.9 Torsional moment Vs Angle of twist of BTROG1



4.1.10BEAM (BTROG2):-

This was a retrofitted Beam with Two Rectangular Openings following 2nd scheme of application of GFRP fabrics i.e., (45/45/45/45/45). The layers made 45^0 with longitudinal axis of beam. The method of application of GFRP fabric was same. The experimental set up and method of testing was same as in previous case. After collapse GFRP sheets were removed and crack pattern of beam was observed.

FIG 4.10Setup of the Beam with GFRP BTROG2

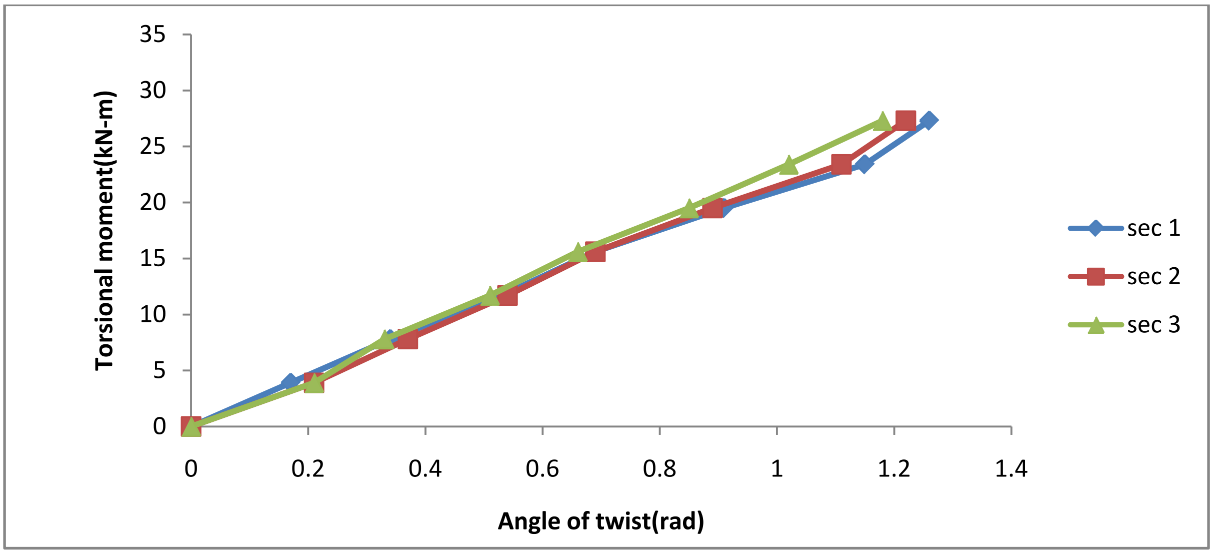
FIG 4.10(b) Crack pattern on one face of BTROG2

FIG 4.10(c) Crack pattern on other face of BTROG2

The first crack was visible at 65 KN load on top face of the beam. The beam failed at 80 KN load i.e. at 31.2 kink torsional moment. Removal of GFRP showed beam type of failure on side accompanied by crushing of concrete. It was observed that the major crack made an angle 50^0 with the longitudinal axis of main beam and 56.25 % increase in torsional moment capacity was obtained.

TABLE 4.10 Torsional Moment vs Angle of Twist for BTROG2:-

Load kN	Torsional moment kN-m	Section 1	Section 2	Section 3	Remarks
0	0	0	0	0	
10	3.9	0.17	0.21	0.21	
20	7.8	0.34	0.37	0.33	
30	11.7	0.53	0.54	0.51	
40	15.6	0.69	0.69	0.66	
50	19.5	0.91	0.89	0.85	
60	23.4	1.15	1.11	1.02	Initial crack 60kN
70	27.3	1.26	1.22	1.18	
80	31.2				Ultimate load 80kN



GRAPH 4.10 Torsional momentVs Angle of twist of BTROG2

4.1.11 BEAM (BTROG3):-

In two rectangular opening beam, GFRP sheet is applied for strengthening the beam under torsional loading .total four layers were applied in bidirectional [90/45/90/45] in this beam also one layer is applied in 90^0bidirectionally and another was in 45^0bidirectionallyfor whole opening portion of the beam one after another layer is applied as shown in figure and the opening dimensions is same as in beam BTRO. Beam BTROG3 is two circular opening in a beam with GFRP as shown in fig. This beam was casted and tested to study effect of the beam with two circular opening in a beam with torsional loading. Strengthening was done with GFRP of 4 layers in $[90/45]_2$ to this beam.

FIG 4.11(a)Beamwith GFRP (BTROG3)

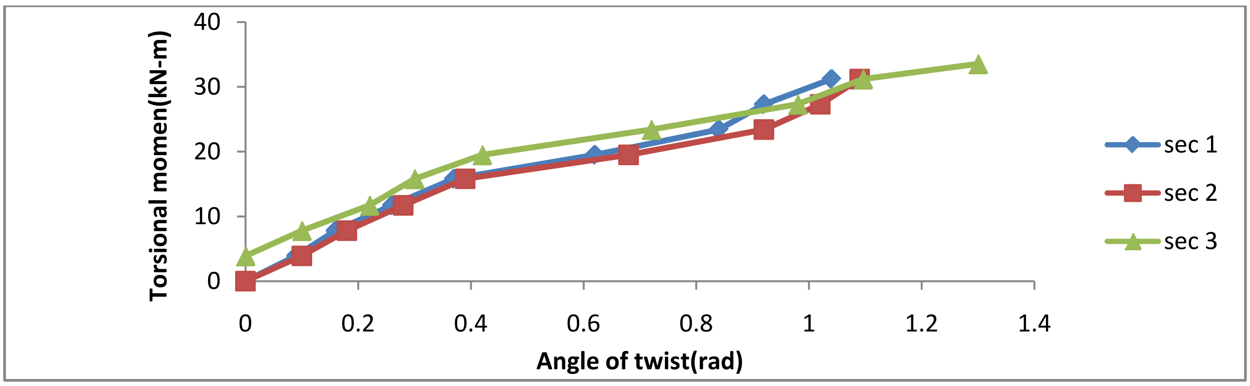
b) Crack pattern on one face of BTROG3

FIG 4.11(c) Crack pattern on other face of BTROG3

The first hair line crack initiated at load of 70 kN the crack was observed at the top side of the beam which was not covered with GFRP and later cracks were developed through the opening of the main beam i.e., through the GFRP. The beam ultimately failed at 87 kN load i.e. at 33.93 kN-m torsional moment. It was observed that the cracks were appeared making an angle 50^0 with the main beam. The cracks were developed through the edges of the opening and inside the opening over the main beam which later leads to the collapse of the beam in torsional loading.

TABLE 4.11 Torsional Moment Vs Angle of Twist for BTROG3:-

Load kN	Torsional moment kN-m	Section 1	Section 2	Section 3	Remarks
0	0	0	0	0	
10	3.9	0.09	0.10	0.14	
20	7.8	0.16	0.18	0.22	
30	11.7	0.26	0.28	0.30	
40	15.6	0.37	0.39	0.42	
50	19.5	0.62	0.68	0.72	
60	23.4	0.84	0.92	0.98	
70	27.3	0.92	1.02	1.09	Initial crack at 70kN
80	31.2	1.04	1.09	1.30	
87	33.93				Ultimate failure at 87kN



GRAPH 4.11 Torsional moment Vs Angle of twist of BTROG3

4.2 COMPARISONS:-

Table 4.12 Torsion Capacity of Beams

S.NO	Beam	Load kN	Torsional moment kN-m	Percentage Decrease / Increase
1	CB	86	33.54	0
2	BSCO	78	30.42	-9.3%
3	BTCO	68	26.52	-20.9
4	BSRO	66	25.74	-23
5	BTRO	35	13.65	-59.3
6	BTCOG1	75	29.25	-12.7
7	BTCOG2	85	33.15	-1.16
8	BTROG1	70	27.30	-18.6
9	BTROG2	80	31.20	-6.9
10	BTCOG3	90	35.10	4.65(increased)
11	BTROG3	87	33.93	1.14(increased)

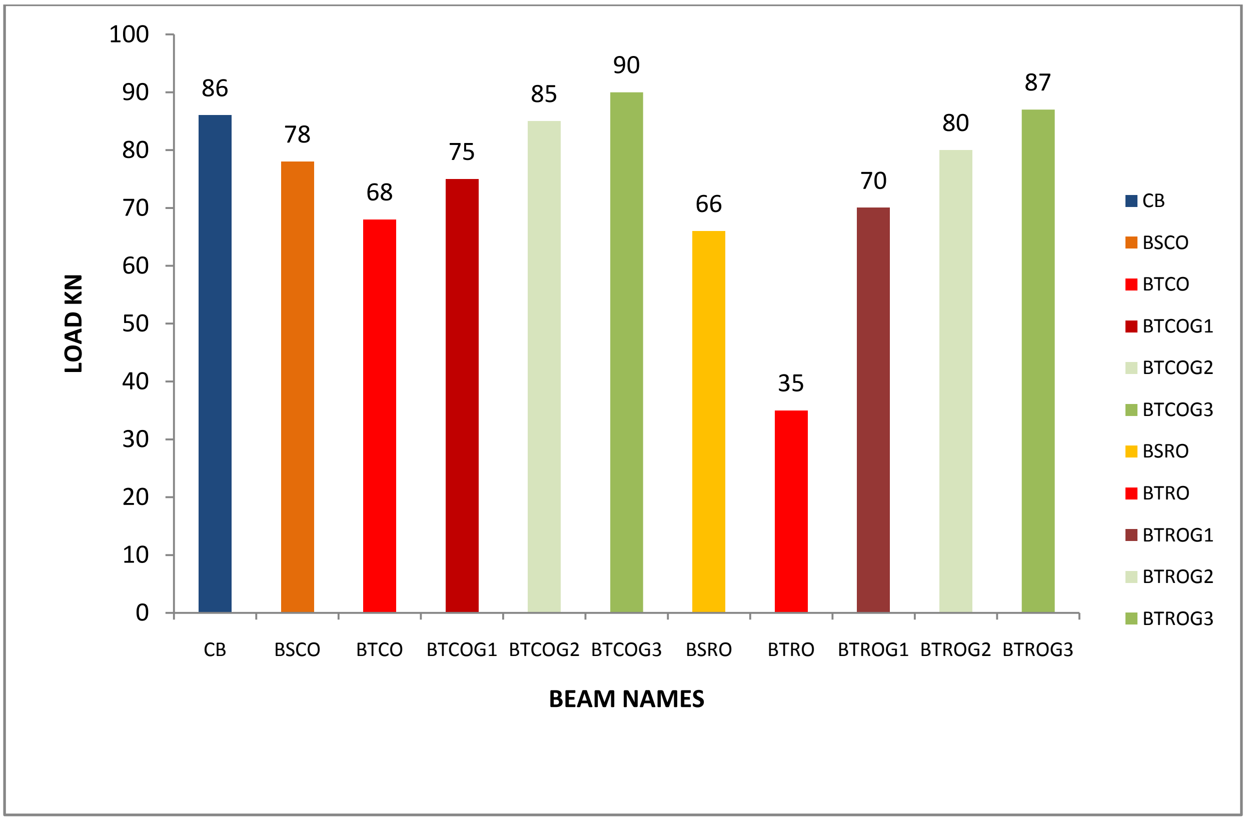


Table 4.13 Torsion Capacity for Retrofitted beams with two circular openings

S.NO	Beam	Load kN	Torsional moment kN-m	Percentage increases when compared with BTCO
1	BTCO	68	26.52	0
2	BTCOG1	75	29.25	9.3%
3	BTCOG2	85	33.15	20%
4	BTCOG3	90	35.10	24.4%

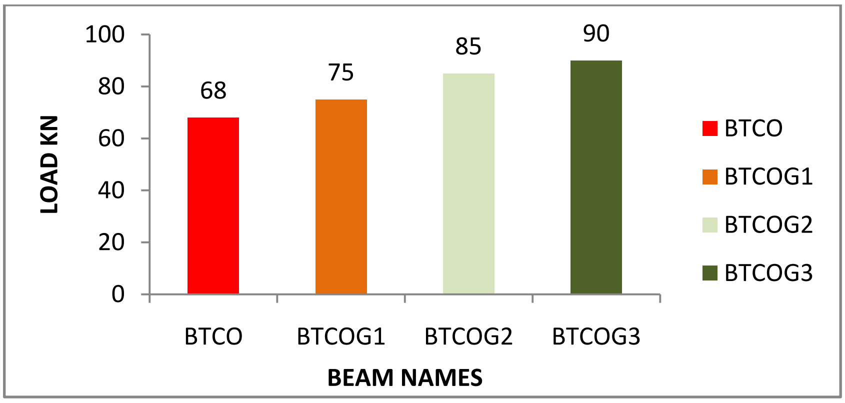
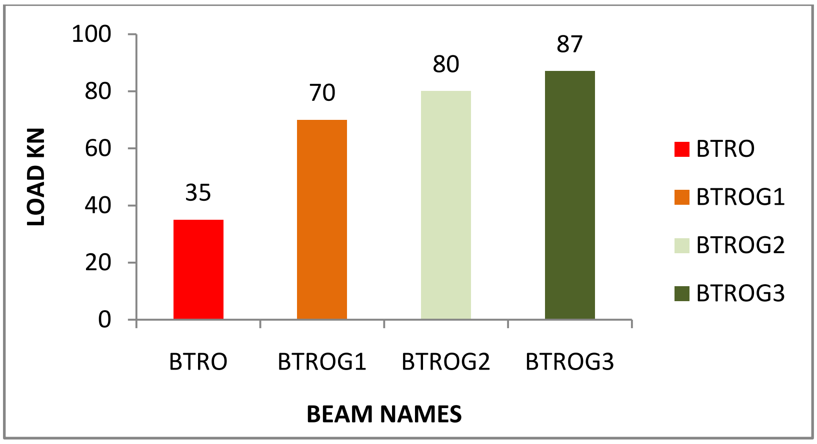
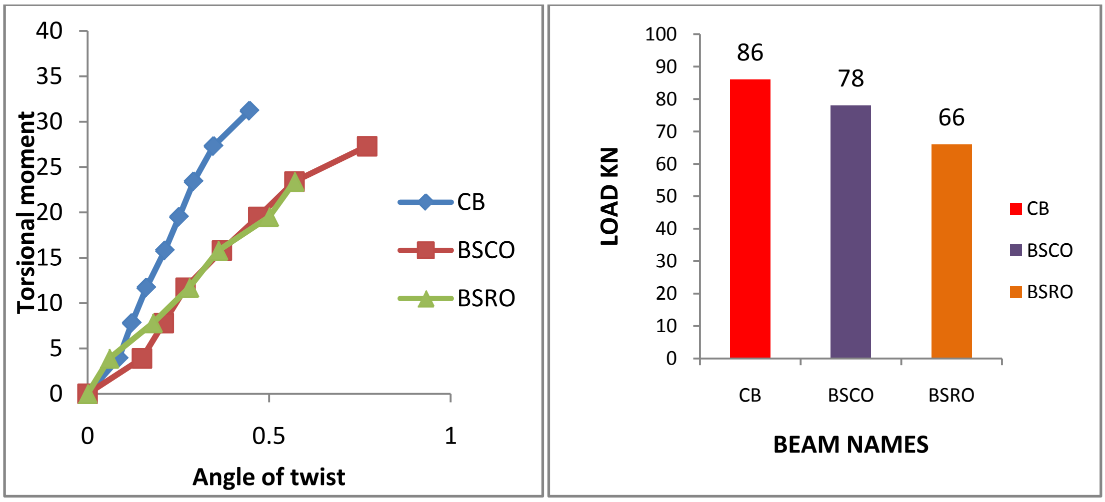


Table 4.14 Torsion Capacity for Retrofitted beams with two rectangular openings

S.NO	Beam	Load kN	Torsional moment kN-m	Percentage increases when compared with BTRO
1	BTRO	35	13.65	0
2	BTROG1	70	27.30	50%
3	BTROG2	80	31.20	56.25%
4	BTROG3	87	33.93	59.7%



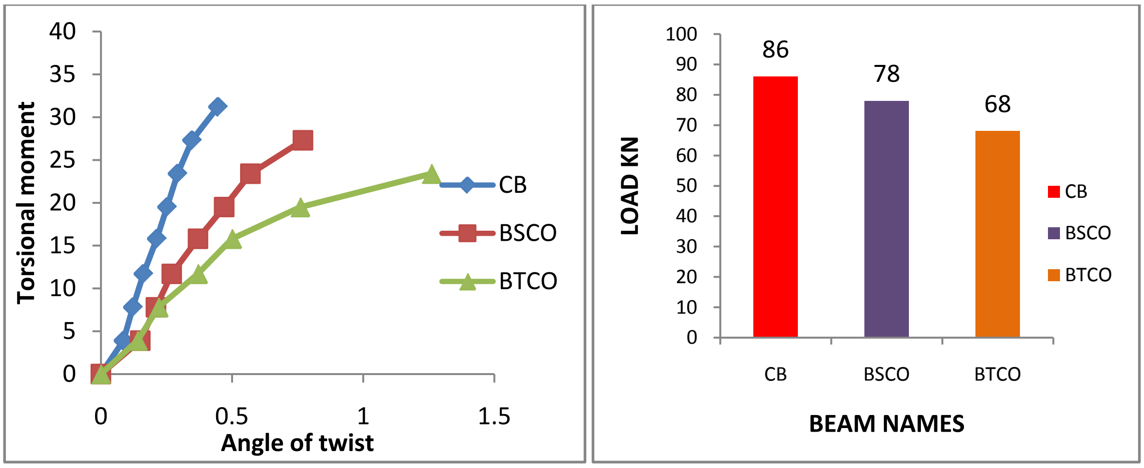
4.2.1 Comparisons of Un-strengthen beams (CB,BSCO,BSRO)



GRAPH 4.12 Comparisons for beams CB, BSCO, and BSRO

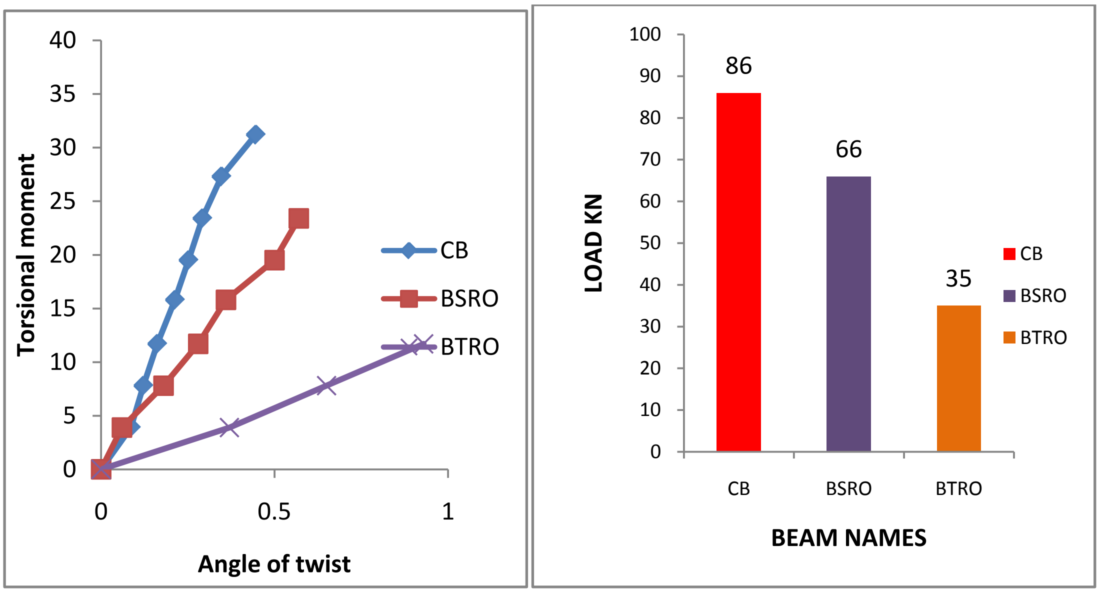
The comparison of beams with single circular and rectangular with control beam exhibited that there is decrease in torsional moment capacity of beams. The reduction is more for rectangular opening. This may be due to more stress concentration at corners of the rectangular opening. Due to reduction in stiffness in both beams with openings BSCO & BSRO more deflection were observed than control beam.

4.2.2 Comparisons of Un-strengthen beams with circular opening



GRAPH 4.13 Comparisons of beams CB, BSCO, and BTCO

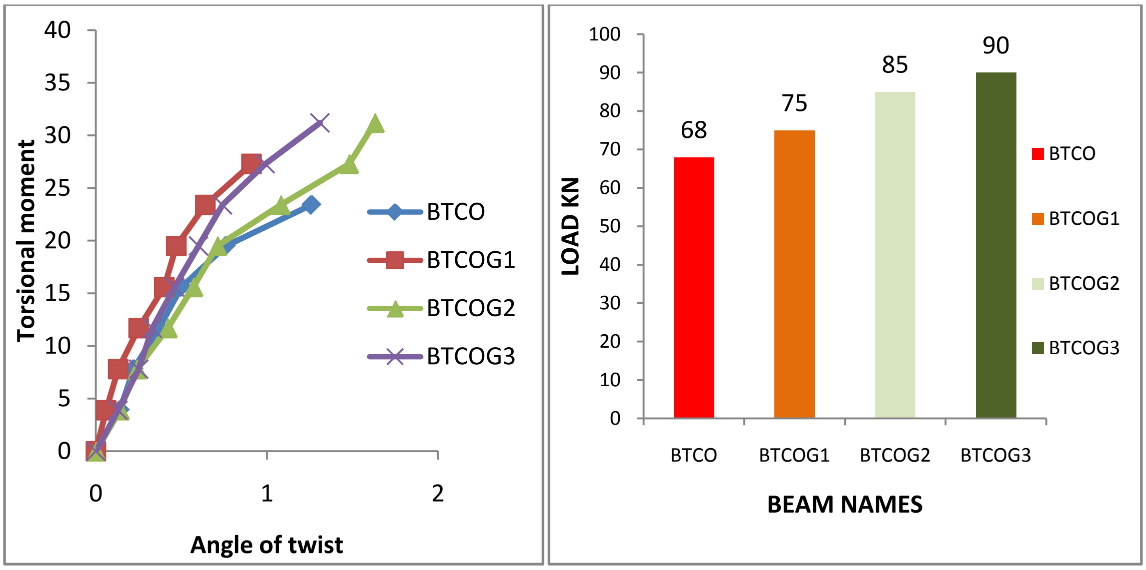
4.2.3 Comparisons of Un-strengthen beams with rectangular opening



GRAPRH 4.14 Comparisons for beams CB, BSRO, BTRO

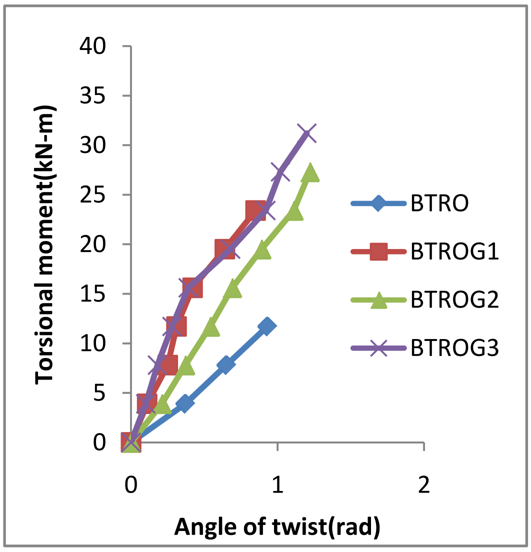
The comparison indicates decrease in torsion moment capacity with increase in no of openings for both circular and rectangular openings.

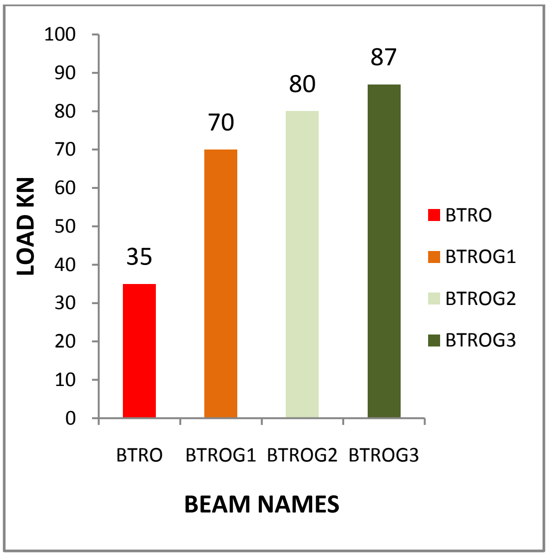
4.2.4 Comparisons of Strengthen beams with circular opening



GRAPH 4.15 Comparisons of beams BTCO, BTCOG1, BTCOG2, and BTCOG3

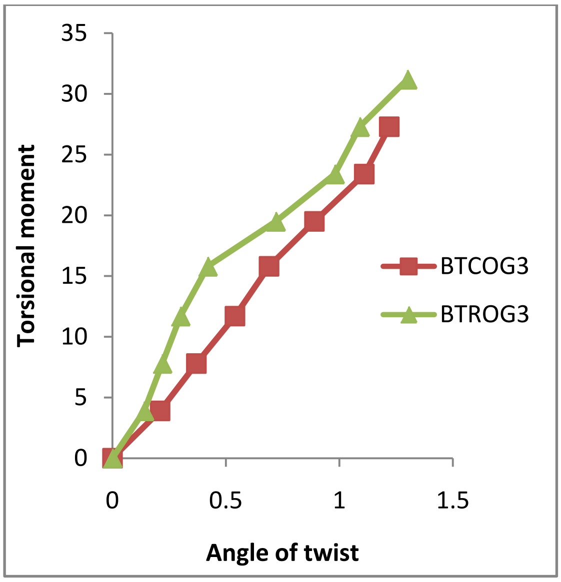
4.2.5 Comparisons of Strengthen beams with rectangular opening

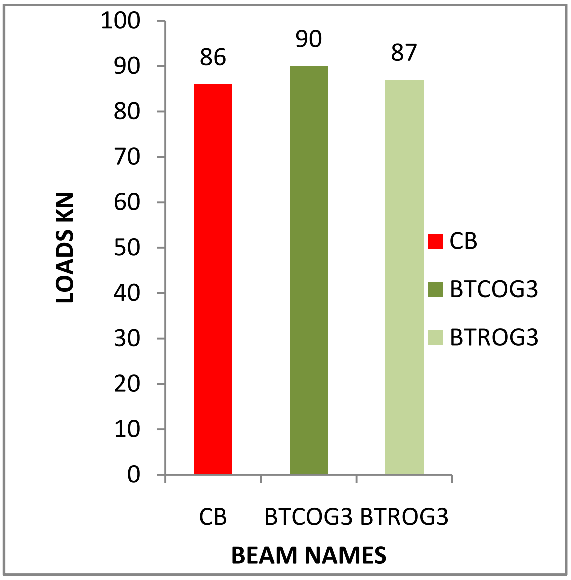




GRAPH 4.16 Comparisons of beams BTRO, BTROG1, BTROG2, and BTROG3

4.2.6Comparisons of Strengthen beams





GRAPH 4.17 Comparisons of beams BTCOG3 and BTROG3

The graphs indicate that U-jacketing the beams with GFRP fabric restore the torsion moment capacity of beams with circular openings in order of 9.3% to 24.4% and beams with rectangular opening in order of 50 % to 59.7% depending on the orientation of fibre in each layer.

The comparison showed that restoration of capacity is maximum for the case 90/45/90/45 scheme than in 45/45/45/45 scheme .It is least for 90/90/90/90 scheme.

The 45^0 fibre orientation scheme provided better option to regain andto increase the torsional capacity of beams with openings.

Out of the three schemes considered 45/45/45/45 orientation scheme provide higher ductility.

Post cracking stiffness of the beam with 90/90/90/90 scheme is much higher than the remaining two.

The orientation scheme 90/45/90/45 is best option for retrofitting the beam with openings because it provides maximum restoring torsion capacity and considerable higher ductility.

CHAPTER 5

NUMERICAL STUDY

Themodified ACItorsion equation proposed Mansur, M.A. and Hasnat[3]by for a rectangular beam with circular and rectangular openings is

$$Tpch = 2\sqrt{fc'}b^2h\left(1 - \lambda\frac{\mathrm{d0}}{\mathrm{h}}\right)$$

$T_{pch=}$ Torsional strength of plain concrete

Where f'_c= cylinder compressive strength b and h =width and depth of the beam.

$\lambda = \cos 45^0$for a circular opening and1 for a rectangular opening.

d_0 = Diameter of opening.

The torsional strength of a reinforced concrete beam with opening is

$T_h = T_{ch} + T_{sh}$

$T_{ch=}$ Torsional strength of plain concrete $T_{sh=}$ Torsional strength provided by stirrups

In the present study stirrups were not provided ,hence this contribution is zero.

$T_h = T_{ch}$

Table 5.1Comparison on Experimental with Theoretical Torsional Moment of Circular and Rectangular Openings

s.no	**Beam**	**Opening diameter d_0 mm**	**Ratio $d_{0/h}$**	**Cylinder compressive strength f'_c N/mm^2**	**Experimental torsional moment T_{exp} N/mm^2**	**Theoretical torsional strength T_{theo} N/mm^2**	**Ratio $= \frac{Texp}{Ttheo}$**
1	BSCO	100	0.26	20.40	30.42	36.48	0.83
2	BTCO	2 X 100	0.52	26.88	26.52	32.33	0.82
3	BSRO	72	0.23	29.33	25.74	21.92	1.17
4	BTRO	2 X 72	0.47	19.20	13.65	12.21	1.11

The comparison of results indicate that the torsion strength is slightly overestimated for beams with circular openings and under estimated for beams with rectangular openings by using the modified ACI torsion equation proposed Mansur, M.A. and Hasnat[3].

CHAPTER 6

CONCLUSIONS

Following conclusions are drawn from the present study

1. Web openings in beams cause reduction in torsion moment capacity and increase in deflections because of reduction in stiffness. Reduction increases with no of openings.
2. The reduction is more for rectangular opening. This may be due to more stress concentration at corners of the rectangular opening.
3. Beam with circular opening exhibited a **Frame type** of failure, because stress concentration across the opening is uniform at edges of openings.
4. Beam with rectangular opening exhibited a **Beam type** of failure, because maximum stress concentration occurs at corners of the openings.
5. All schemes of retrofitting exhibited increase in torsion capacity of beams with openings.U-jacketing the beams with GFRP fabric restore the torsion moment capacity of beams with circular openings in order of 9.3% to 24.4% and the beams with rectangular opening in order of 50 % to 59.7% depending on the orientations of fibers in each layer.
6. Retrofitting is more effective for beams with rectangular opening.
7. Out of the three schemes considered [45/45/45/45] orientation scheme provide higher ductility.
8. Stiffness of the beam with [90/90/90/90] scheme is higher than the remaining two..
9. The [90/90/90/90] scheme provides more stiffness and [45/45/45/45] provides ductility, combination of these two i.e. [90/45/90/45] provides better ductility with more restoring torsion capacity.
10. The orientation scheme [90/45/90/45] is best option for retrofitting the beam with openings because it provides maximum restoring torsion capacity and considerable higher ductility.
11. The comparison of experimental results with theoretical results , calculated by using the modified ACI Code torsion equation proposed Mansur, M.A. and Hasnat[3] , shows that the torsion strength is slightly overestimated for beams with circular openings and underestimated for beams with rectangular opening.

CHAPTER 7

REFERENCES

1. Hasnat, A. and Akhtaruzzaman, A.A., Beams with Small Rectangular Opening under Torsion,Bending and Shear, *Journal of the Structural Division, American Society of Civil Engineers,* 113(10): 2253-2270 (1987).

2. ACI Committee 318, *Building Code Requirements for Reinforced Concrete (ACI*318-83), American Concrete Institute, Detroit, 111 p. (1983).

3. Mansur, M.A. and Hasnat, A., Concrete Beams with Small Opening under Torsion, *Proceedings, American Society of Civil Engineers,* 105(ST 11): 2433-2447 (1979).

4. Somes, N.F. and W.G. Corley, Circular openings in webs of continuous beams. American Concrete Institute. Detroit, MI, pp: 359-398, (1974).

5. Hsu, T.T.C., Ultimate Torque of Reinforced Rectangular Beams, Journal ofthe Structural Division, American Society of Civil Engineers, 94(S1'2): 485-510 (1968).

6. Hsu, T.T.C., Torsion of Structural Concrete - Behavior of Reinforced Concrete Rectangular Members*, in: Torsion of Structural Concrete, ACI Special Publ. SP-IB,* pp. 261-305 (1968).

7. Mansur, M.A. and Hasnat, A., Concrete Beams with Small Opening under Torsion, *Proceedings, American Society of Civil Engineers,* 105(ST 11): 2433-2447 (1979).

8. Mansur, M.A. and Paramasivam, P., Reinforced Concrete Beams with a Small Opening in Bending and Torsion, *Journal of the American Concrete Institute,* Proceedings, and 81(2): 180-185 (1984).

9. Mansur, M.A., Combined Bending and Torsion in Reinforced Concrete Beams with Rectangular Openings, *Concrete International: Design* &*Construction,* 5(11): 51-58 (1983,2006).

10. Hasnat, A. and Akhtaruzzaman, A.A., An Experimental Investigation to Determine the Ultimate Strength of Reinforced Concrete Beams Containing an Opening under Bending and Torsion, *Final Report, Research Project No. 01-21*, *Scientific Research*

Administration, Faculty ofEngineering, KingAbdulaziz University, Jeddah, Saudi Arabia, pp. 1-74 (1983).

11. Hasnat, A. and Akhtaruzzaman**,** A.A., Reinforced Concrete Beams with a Small Rectangular Openingunder Torsion, Bending and Shear, *Journal, Structural Division, American Society of Civil Engineers,*113 (10): 2253-2270 (1987).

12. Meier,U., and Kaiser,H.**"**Strengthening of structures with CFRP laminates."Advanced composites materials in civil engineering structures,S>L>Iyer,ed.,Am.Soc. ofCiv.Engrs., New York,N.Y.,224-232,(1991).

13. Mertz, D., et al. ... Rubinsky, I.A., and Rubinsky, A."An Investigation into the Use of Fiber-Glass for Prestressed".(1954).

14. SoroushAmiri, Reza Masoudnia "Investigation of the Opening Effects on the Behaviour of Concrete Beams Without Additional Reinforcement in Opening Region Using Fem Method"; Australian Journal of Basic and Applied Sciences, 5(5): 617-627, 2011 ISSN 1991-8178.

15. Ameli, M. and Ronagh, H.R. "Behavior of FRP strengthened reinforced concrete beams under torsion",Journal of Composites for Construction, 11(2), 192-200,(2007)

16. Hanson, J. M. "Square openings in webs of continuous joists."(RDOOIJ)fD, Portland Cement Association, Skokie. Ill. (1969).

17. Salam, S. A. Beams with openings under different stress conditions. Proc., 3rd Conference on Our World in Concrete and Structures, CI-Premier, Singapore, 25-26 Aug., 259-267. (1977).

18. Abdalla, H.A., A.M. Torkeya, H.A. Haggagb and A.F. Abu-Amira,; "Design against cracking at openings in reinforced concrete beams strengthened with composite sheets. Composite Structures".

19. Gobarah A., Ghorbel M., and Chidiac, S. "Upgrading torsional resistance of RC beams using FRP." Journal of Composites for Construction,6,257–263. (2002).

20. Panchacharam, S. and Belarbi, A. "Torsional behaviour of reinforced concrete beams strengthened with FRP composites", Proceedings 1st FIB Congress, Osaka, Japan, 1-10. (2002).

21. Rahal K. N., and Collins,M. P.,"Analysis of Sections Subjected to Combined shear and torsion-A theoretical Model," ACI Structural journal,V.92,No.4,July-Aug. 1995,pp. 456-469.

22. SoroushAmiri, Reza Masoudnia and Ali Akbar Pabarja; "The Study of the Effects of Web Openings on the Concrete Beams"; Australian Journal of Basic and Applied Sciences.

23. Siao, W.B. and Yap, S.F. Ultimate behaviour of unstrengthen large openings made in existingconcrete beams. Journal of the Institution of Engineers. 30(3): 51-57. (1990).

24. Allam, S.M., Strengthening of RC beams with large openings in the shear zone. AlexandriaEngineering Journal, 44(1): PP: 59-78. (2005).

25. Amiri, S., R. Masoudnia, Investigation of the opening effects on the behavior of concrete beamswithout additional reinforcement in opening region using FEM method, Australian Journal of Basic and AppliedSciences, 5(5): 617-627. (2011).

26. Zojaji A.R. and Kabir M.Z. "Analytical approach for predicting full torsional behavior of reinforced concrete beams strengthened with FRP materials". ScientiaIranica A.19 (1), 51–63. (2011)

27. Hanson, J.M., Square openings in webs of continuous joists. Portland Cement Association., PP: l-14. (1969).